Measuring Masses of Stellar Black Holes

Masses of black holes in binaries can be constrained; unlike neutron stars, black holes (themselves) don't pulse (though their accretion disks may produce variable X-ray emissions)

Construct mass functions for single-lined binaries; look for large mass functions

Try to constrain mass of the companion spectroscopically to constrain mass of the compact object

$M_{CO} > M_{max,\,NS}$ => Black Hole

Masses of Stellar Black Hole Candidates

Binary	Likely $M_X(M_\odot)$	$f(M)=M_{X,min}(M_\odot)$
4U1543-47	5 ± 2.5	0.22 ± 0.02
GRO J0422+32	10 ± 5	1.21 ± 0.06
GRO J1655-40	7 ± 1	2.73 ± 0.09
SAX J1819.3-2525	10.2 ± 1.5	2.74 ± 0.12
A0620-00	10 ± 5	2.91 ± 0.08
GRS 1124-683	7 ± 3	3.01 ± 0.15
GRS 1009-45	4.2 ± 0.6	3.17 ± 0.12
H1705-250	4.9 ± 1.3	4.86 ± 0.13
GS 2000+250	10 ± 4	4.97 ± 0.10
XTE J1118+480	7 ± 1	6.0 ± 0.3
GS 2023+338	12 ± 2	6.08 ± 0.06
XTE J1550-564	10.5 ± 1	6.86 ± 0.71
XTE J1859+226	10 ± 3	7.4 ± 1.1
GRS 1915+105	14 ± 4	9.5 ± 3.0

http://cgpg.gravity.psu.edu/events/conferences/Gravitation_Decennial/Proceedings/Plenaries/Sunday/Narayan/narayan_plenary.pdf

Measuring the Spin of a Black Hole

For a black hole material outside event horizon up to some limit can orbit stably around the black hole.
This limit called the Innermost Stable Circular Orbit, r_{ISCO}

$$
\begin{aligned}
r_{ISCO} &= M(3 + Z_2 \mp [(3 - Z_1)(3 + Z_1 + 2Z_2)]^{1/2} \\
Z_1 &= 1 + (1 - a^{2/M^2})^{1/3}[(1 + a/M)^{1/3} + (1 - a/M)^{1/3}] \\
Z_2 &= (3a^2/M^2 + Z_1^2)^{1/2}
\end{aligned}
$$

In the Kerr Metric,

$$\Omega = \pm \frac{\sqrt{M}}{r^{3/2} \pm a M^{1/2}}$$

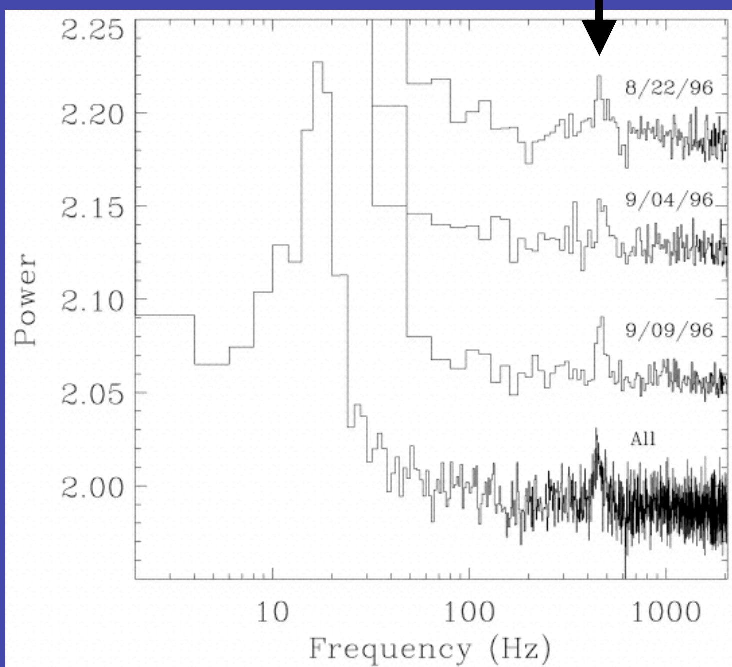
(Shapiro & Teukolsky 12.7.19)

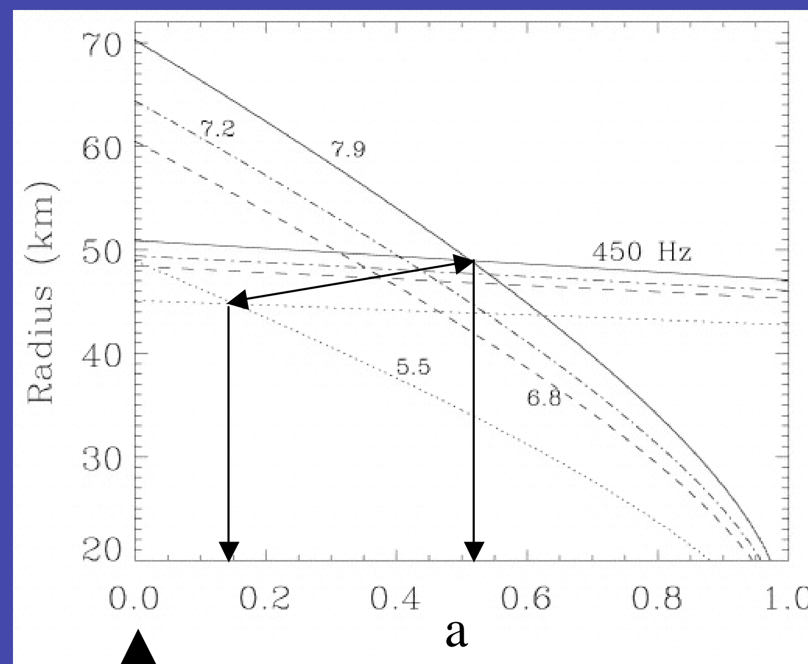
So the highest periodic signal from a BH can occur near r_{ISCO}; measure M_{BH}, then can deduce *a*, the specific angular momentum of the BH

Example: GRO J1655-40 (Nova Sco 1994)

$5.5M_O < M_{BH} < 7.9\ M_O$

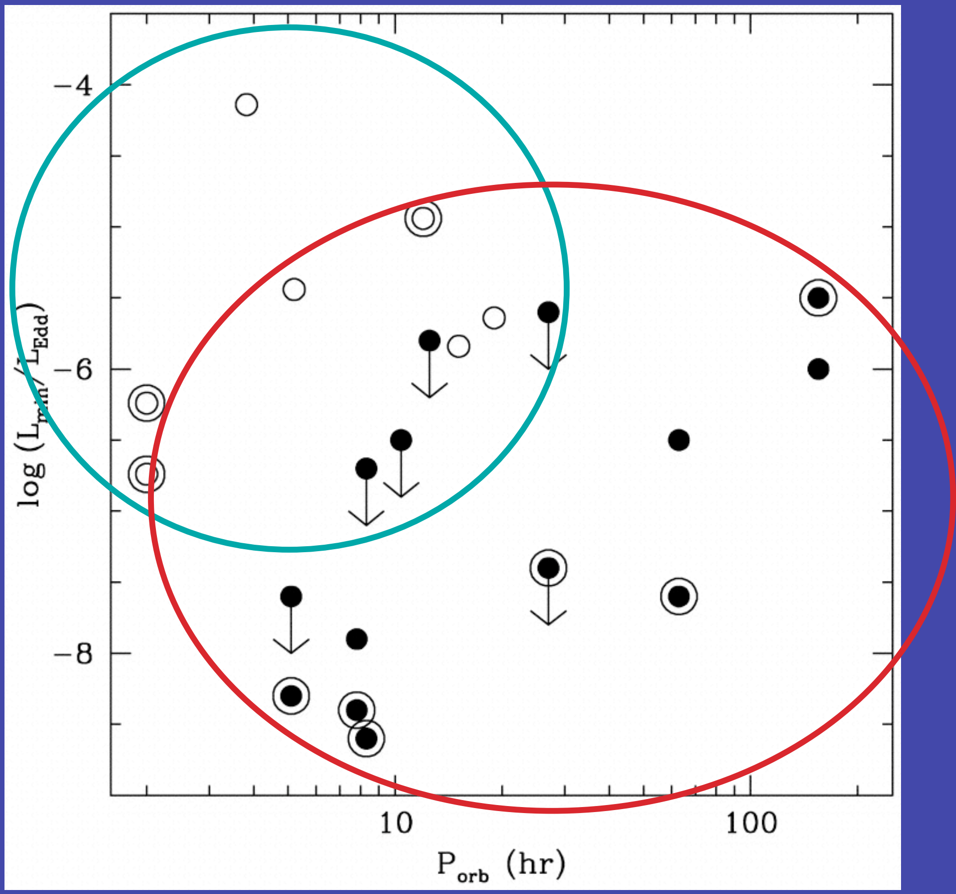
This X-ray binary was observed with RXTE and found to have a "quasi-periodic oscillation" with a frequency of 450 kHz





a=0: ruled out

Event Horizons found?



Quiescent luminosities of BHXNs (filled circles) and NSXNs (open circles) from Garcia et al. 2001

X-ray luminosity of X-ray Novae containing neutron stars in quiescence were compared to X-ray luminosity of XRNs containing BHs.

- BH systems were subluminous compared to NS systems.
- BHs hide some of their accretion luminosity behind the event horizon?

ULXs

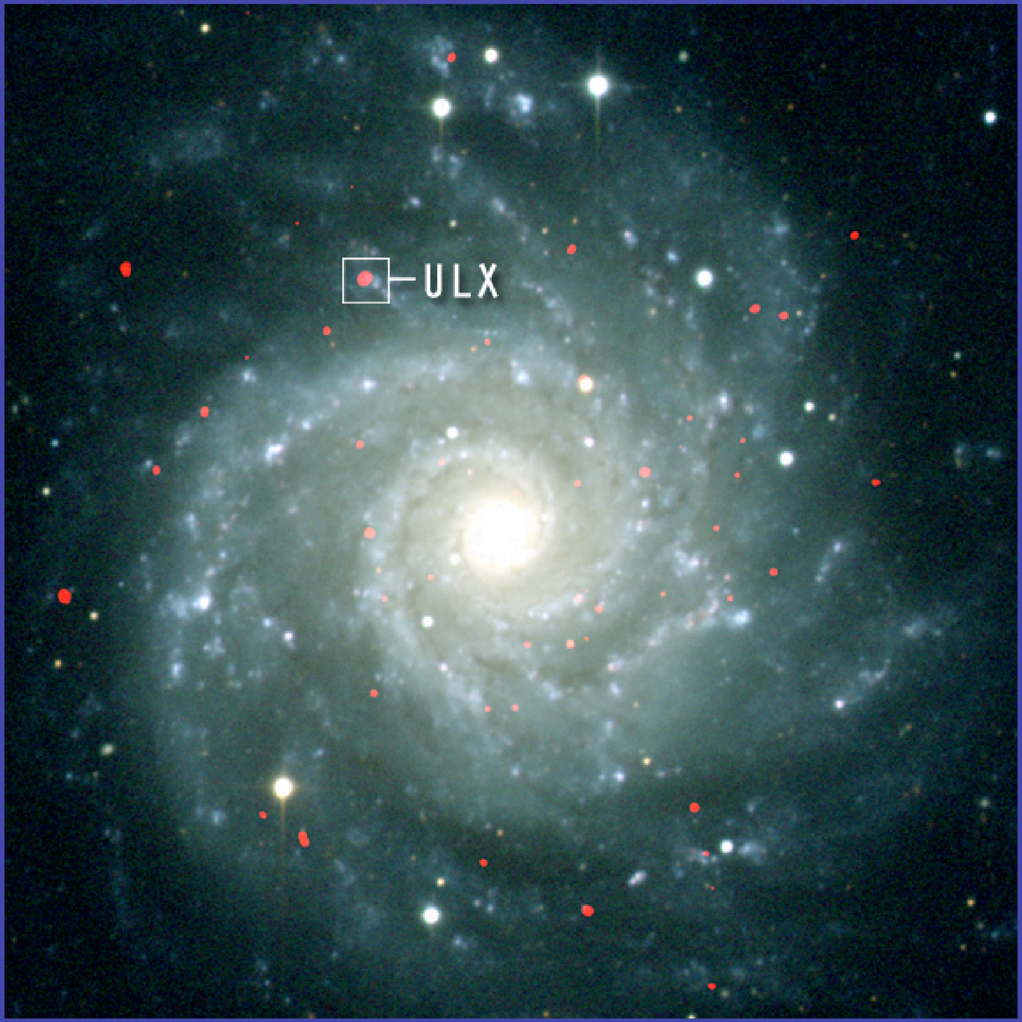
Eddington Limit: Luminosity of an object when its radiation pressure force on electrons equals the force of its self gravity

$$L_E = 4\pi G M m_p c/\sigma_T = 1.2 \times 10^{38} (\frac{M}{M_\odot}) \text{ ergs s}^{-1}$$

ULXs= ultraluminous X-ray sources: compact, off-nuclear X-ray sources with X-ray luminosities in the range of $L_x \sim 10^{39}$ - 10^{41} erg/s, i.e. 10-1000 L_E

About 200 ULXs are known

ULX example: M74



CHANDRA/ACIS sources in red (J.Liu et al. & T.Boroson)

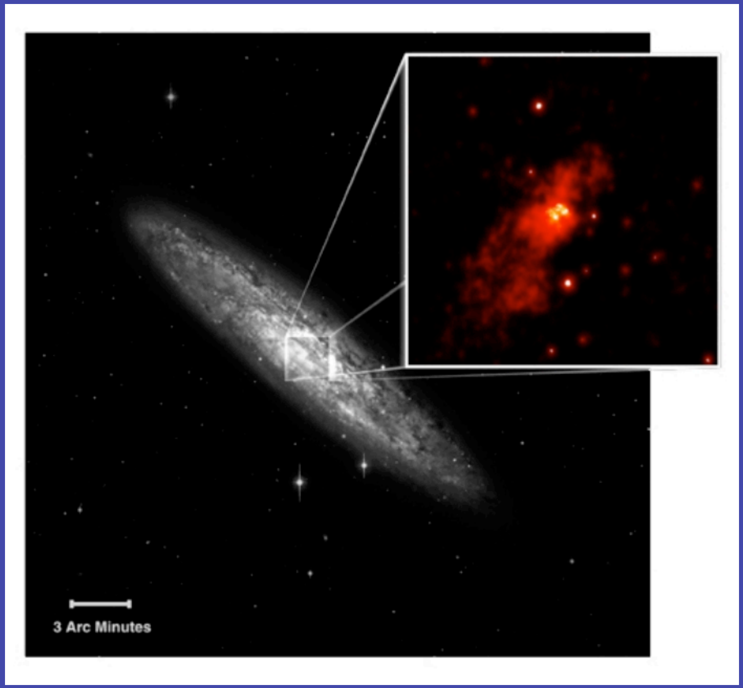
ULX in M74
Quasi-period of 2 hours
100 M_{0} Black Hole?
(probably not an unresolved group of LMXBs)

Intermediate Mass Black Holes

How can BHs with $M > 100\ M_\odot$ form?

too large for normal stellar evolution (with Z>0) since $M_{star}<150\ M_\odot$ (Figer 2005)

Collision of many stellar mass BHs in massive star cluster?

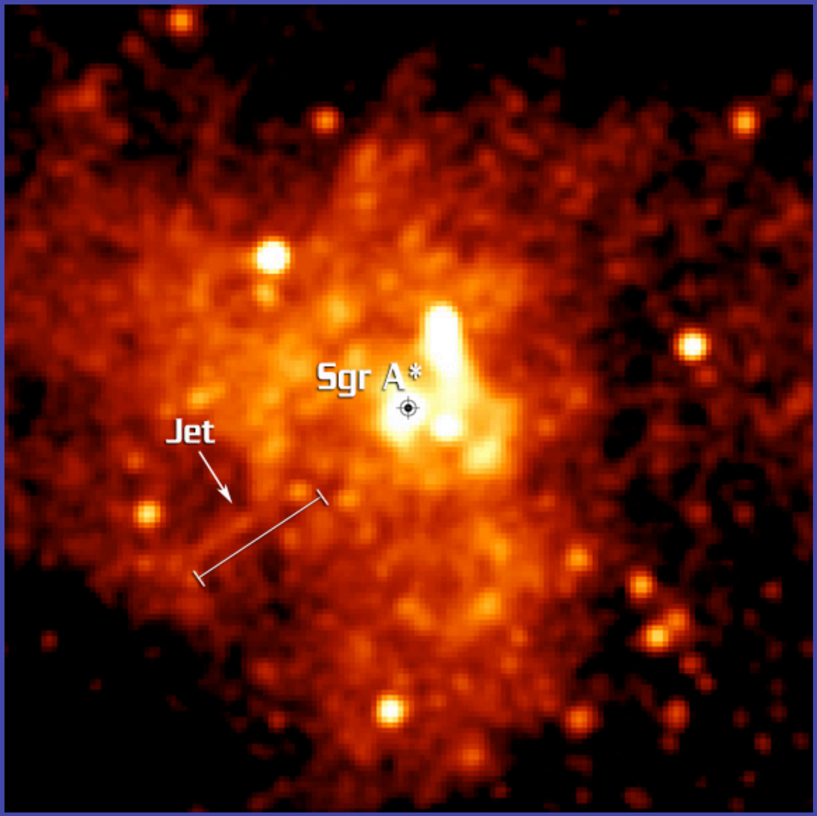


NGC 253

A "starburst" galaxy with 6 ULXs near the center of the galaxy

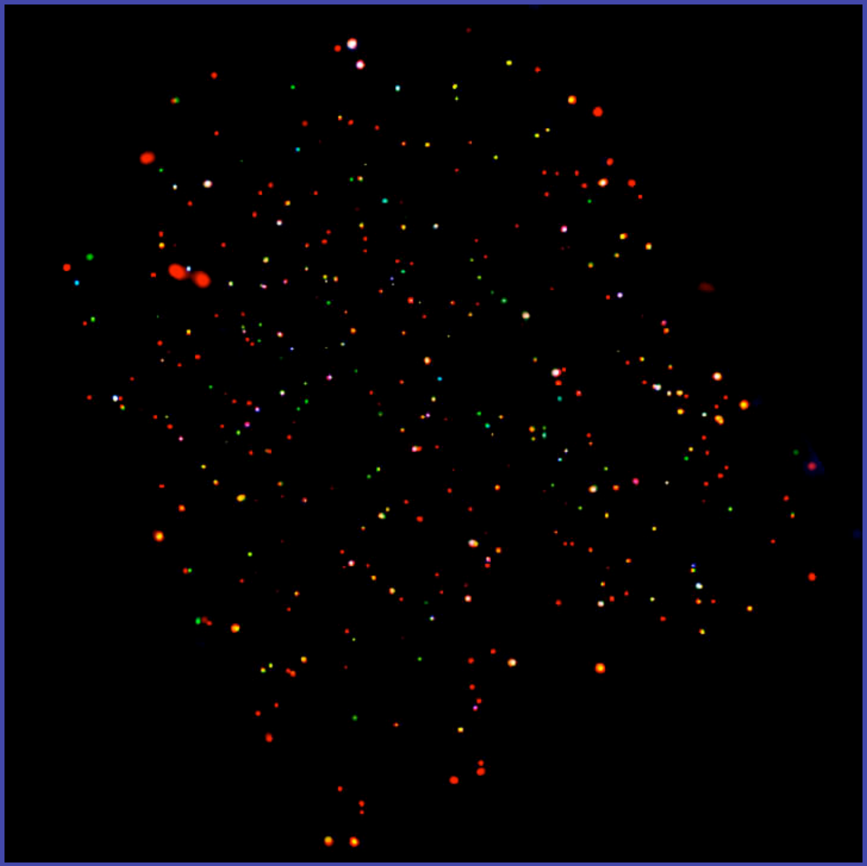
Supermassive Black Holes

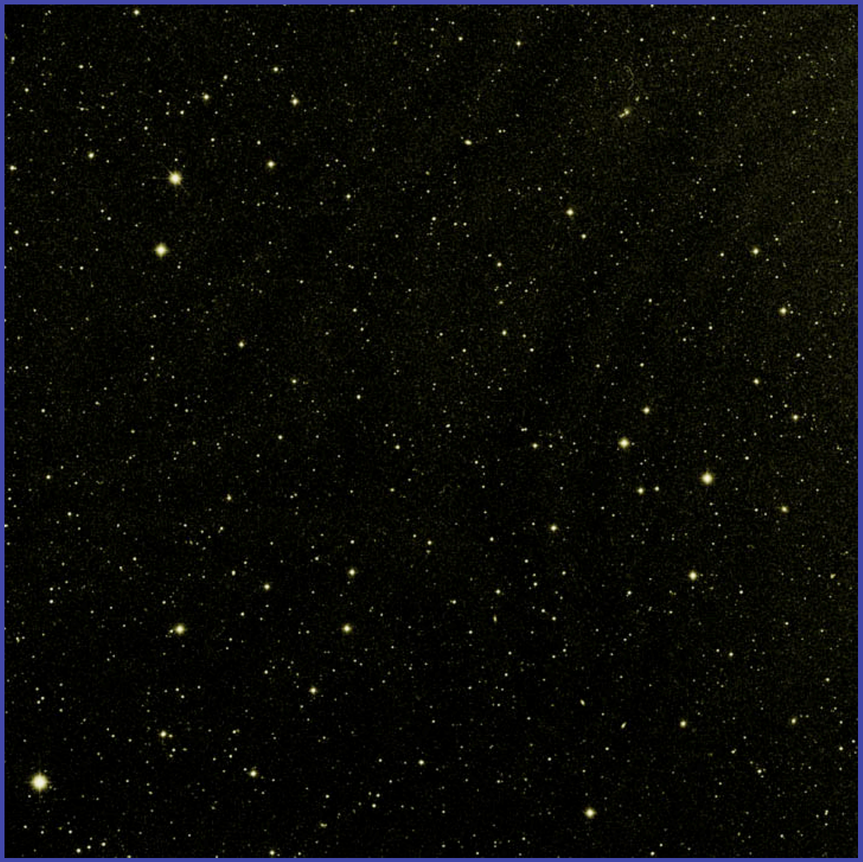
Centers of some types of galaxies seem to house supermassive ($M \sim 10^6\, M_\odot$) black holes



Sgr A* is the Milky Way's supermassive black hole
In the current epoch most SMBHs have low L_x's.
At high redshifts, SMBHs have very large L_x's - dominate bolometric luminosity

SMBH Census





Chandra observations of the “Lockman Hole” (a region of very low Galactic absorption) detects a large number of SMBHs. Found:

- BH activity peaked 6 billion years ago
- Smaller black holes turned on later

Summary

Population of compact objects in our galaxy very uncertain: how many faint ones are there?

COs are prime labs for extremes of physical study (esp. GR, condensed matter)

Most NSs seem to have masses much lower than the upper limit of about 3 Msuns

Black holes can have any mass: lowest mass is about 5 solar masses (no mini-black holes yet)

How do intermediate mass black holes form, if they exist

In the News

Black Holes Don't Exist! - George Chapline, LLNL

http://www.nature.com/physics/physics.taf?file=/physics/highlights/7034-1.html

http://arxiv.org/abs/astro-ph/0503200

- Event Horizons inconsistent with quantum mechanics
- Quantum fluctuations at the event horizon prevent the ultimate collapse to a singularity
- Inside event horizon, space filled with "Dark Energy": Dark Energy Stars
- Would behave like "normal" black hole outside event horizon; inside horizon, material could get thrown out of star
- nucleons decay & turn into positrons which are ejected from the "dark star": Annihilation produces some of the high energy emission associated with black holes
- "Dark energy condensates": form dark matter?

Gamma Ray Bursts (GRBs)

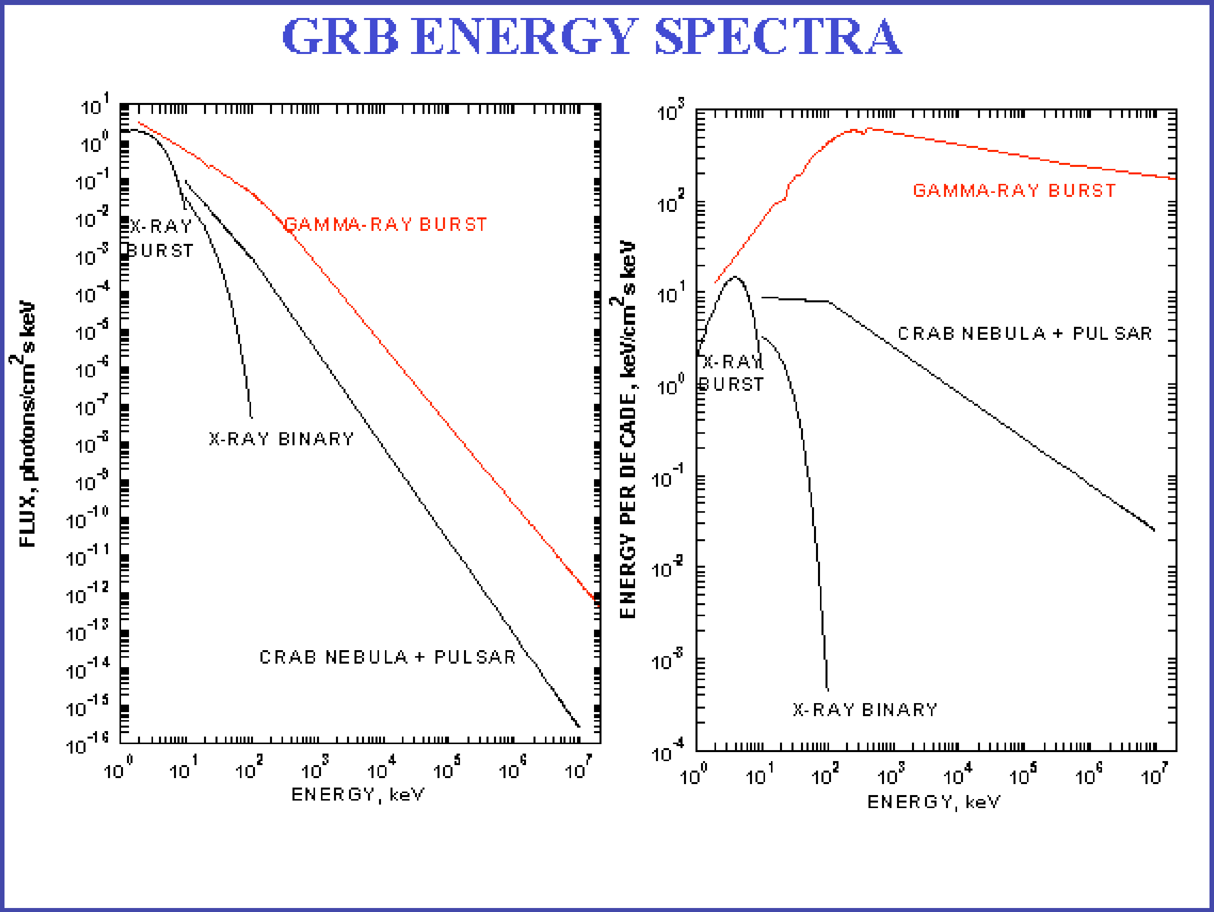
GRB: transient, brief increase in gamma-ray intensity from a localized region of the sky

Typically last < second to minutes

Because Gamma-rays are difficult to focus, GR source positionings are very coarse (typically good fraction of a degree).

- many source counterparts in GRB error boxes
- transient events are by nature difficult to identify (may not be around after the event ends)

Energy Comparison



Models?

- Expanding SN fireball?
- Collapsars/Hypernovae (very massive stars which collapse directly to form BHs)
- Merging NSs
- Magnetic activity around neutron stars
- NS formation
- NS/BH/WD binaries

- “white holes”
- flares
- comet collisions with NSs
- antimatter-matter annihilation
- magnetic bottles in the solar wind
- relativistic dust
- instabilities in vacuum polarization near charged BHs
- etc

Discovery of GRBs

GRBs were discovered as a result of the Nuclear Test Ban Treaty which prohibited nuclear weapon test explosions and any other nuclear explosions in three environments: in the atmosphere, underwater and in outer space.

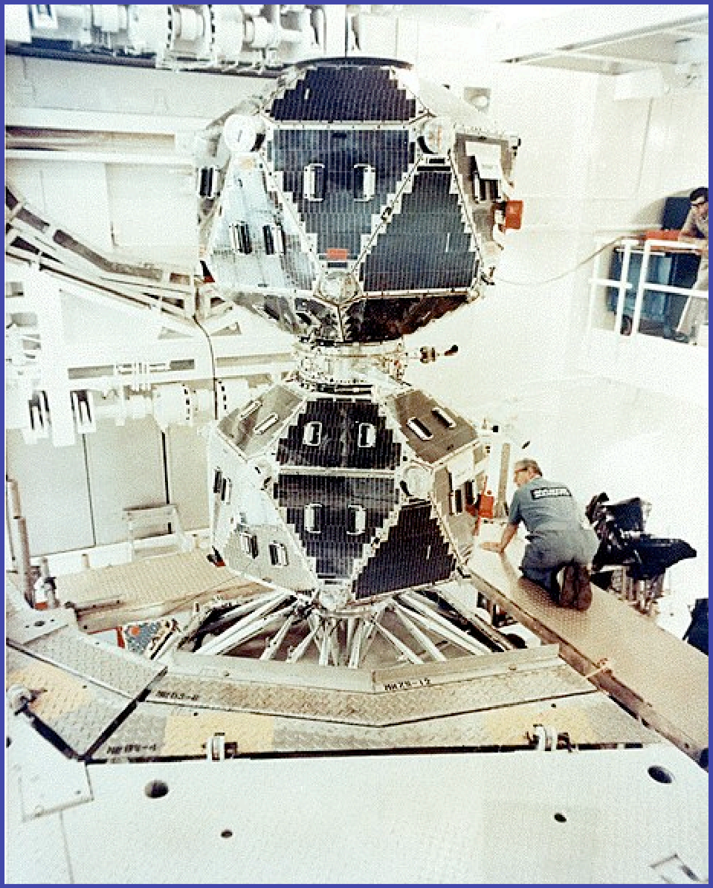
How to verify the treaty: Use detectors sensitive to emission of gamma-rays produced by the blast

Required placing Gamma ray detectors in space

Vela Satellites

Series of 6 satellites – code named Vela (spanish for “watchman”) – with gamma-ray detectors launched in 1963

In checking data from Vela 4 from 1967, scientist at LANL named Ray Klebesadel found (in 1969) “ a spike in the data, a dip, a second spike, and a long, gradual tail off.”



Vela 5B

http://science.nasa.gov/newhome/headlines/ast19sep97_2.htm

Announcement of GRBs

Vela 5 & 6 found many new bursts.

Allowed spatial distribution to be constrained by triangulation between various Vela satellites

Bursts (as suspected) came from outside the solar system. Already, by their random scatter across the sky, the data hinted that the sources were out in the universe rather than in the galaxy.

Announced 1973: 16 bursts

Sample Vela Burst

No. 2, 1973 GAMMA-RAY BURSTS OF COSMIC ORIGIN L87

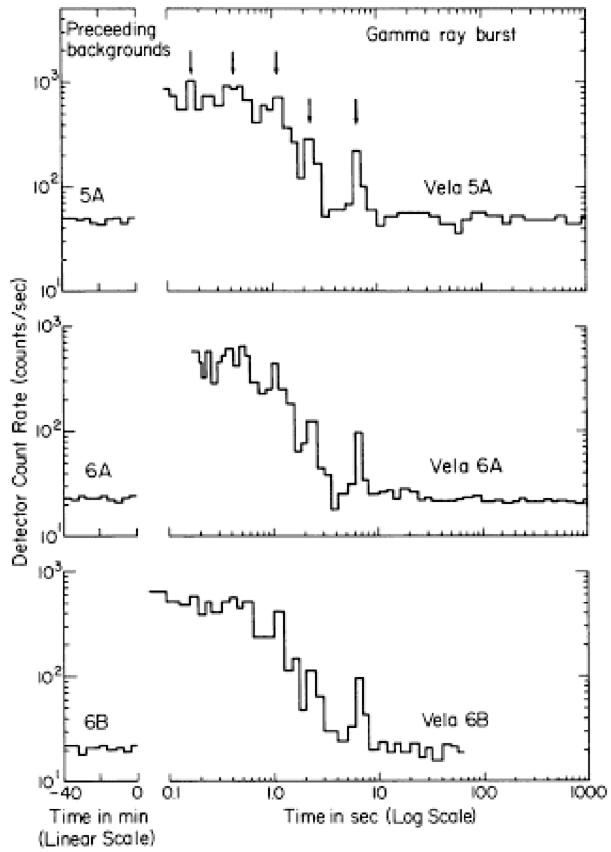


FIG. 1.—Count rate as a function of time for the gamma-ray burst of 1970 August 22 as recorded at three Vela spacecraft. Arrows indicate some of the common structure. Background count rates immediately preceding the burst are also shown. *Vela 5A* count rates have been reduced by 100 counts per second (a major fraction of the background) to emphasize structure.

- •Burst lasts a few minutes, others less than 1 second
- • some show structure (peaks)
- •0.2-1.5 MeV range
- •not correlated with detected supernovae (to within several weeks)
- •“theoretician’s supernovae”?

Unresolved Issues

Source(s) of Bursts? Need energetic sources for abundant production of gamma-rays

- stellar explosions?
- collision of collapsed objects?

Questions:

Do they repeat?

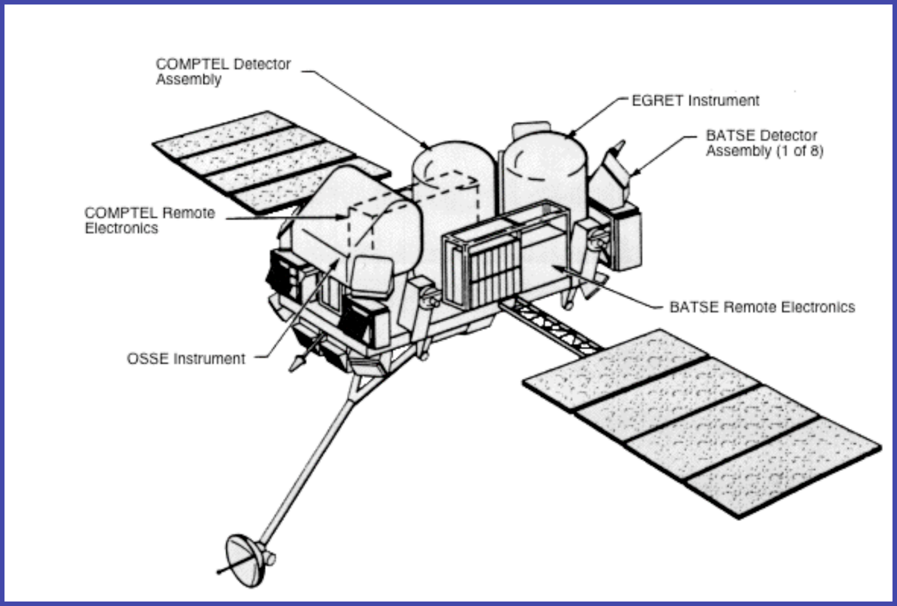
How are they distributed in space? 2 thoughts:

- Local: associated with some population of objects in the Milky Way: Neutron star halo?
- Cosmological: associated with some population of objects at cosmological distances (supermassive black holes in galactic centers? other objects in distant galaxies)?

BATSE

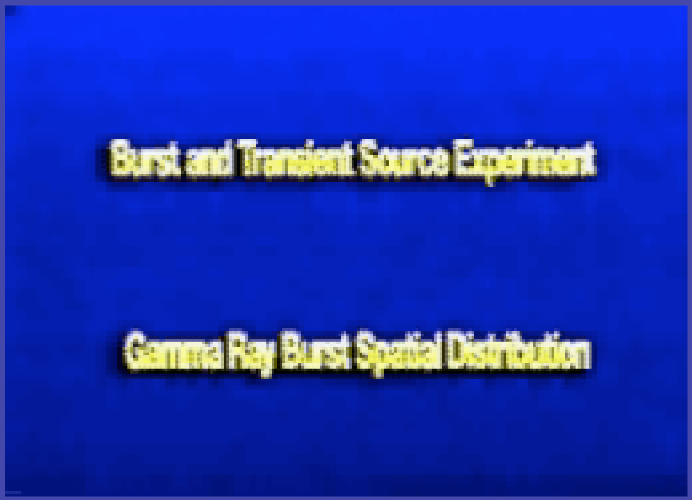
Need a dedicated, sensitive, wide-area gamma-ray observatory with some spatial sensitivity

BATSE (Apr 21 1991-June 4, 2000), the Burst and Transient Source Experiment on the Compton Gamma-ray Observatory, designed to make the next step



8 detectors, allow position determination (to about 5°)
25 keV - 2 MeV

Spatial Distributions



April-Dec 1991

No clustering around Milky Way or other galaxies or galaxy clusters

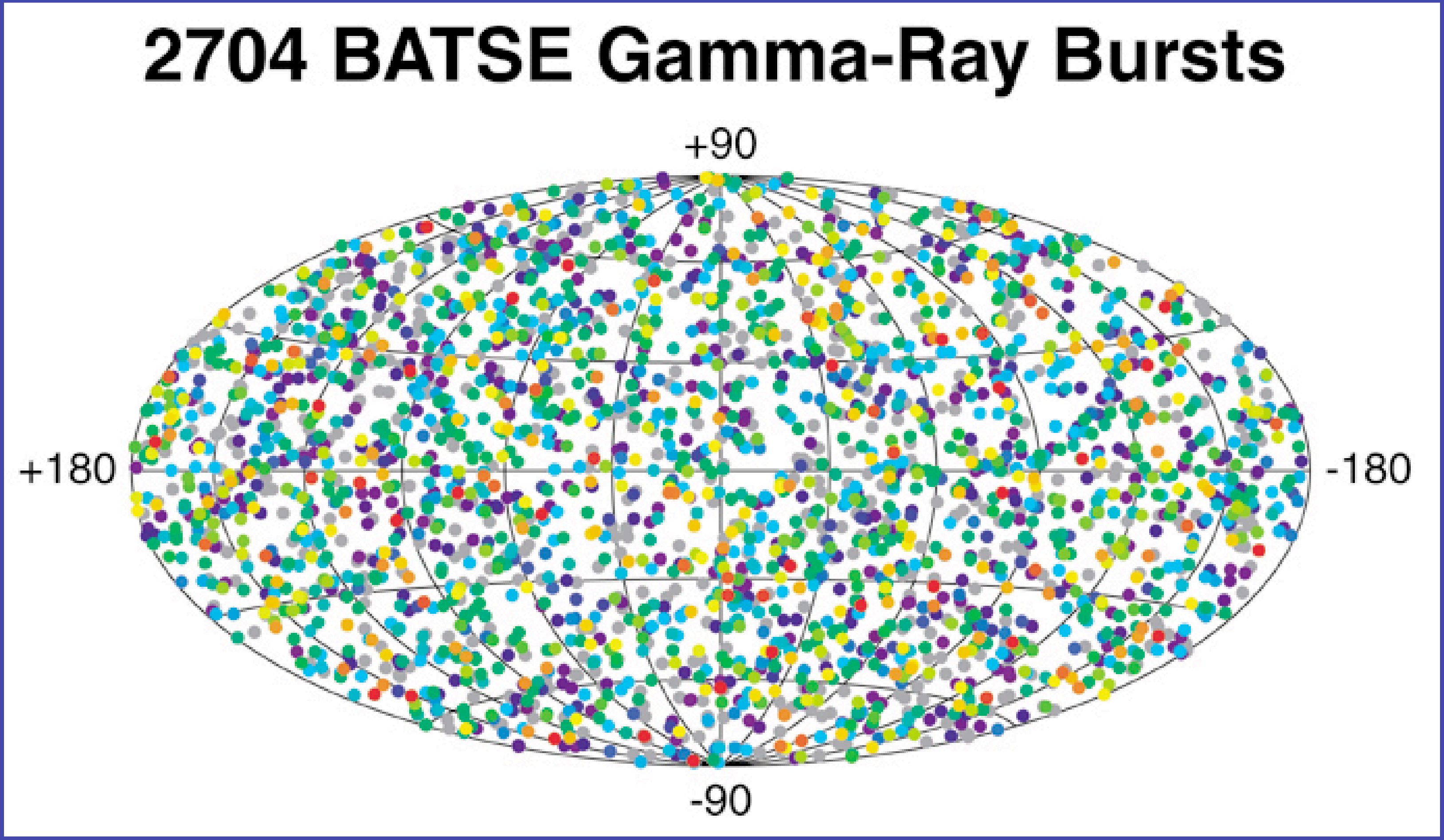
Fewer faint bursts than expected: radial distance limit?

ISOTROPIC DISTRIBUTION
BUT NOT HOMOGENEOUS

In particular, neutron star galactic halo models needed unusual characteristics: $R_{halo} > 50$ kpc with no central concentration

Maybe cosmological population? (isotropic, but not homogeneous because of increasing redshift with increasing distance)

BATSE Bursts: Final Tally



purple: faint burst; red: bright burst

Observational Properties: V/V_{max}

Key property is the distances to bursts: near or far?

The sample of bursts is flux limited (fluxes have to be greater than the limiting BATSE sensitivity) so can characterize the distance distribution by V/V_{max}, where V is the volume that the source appears in, and V_{max} the maximum volume in which the source would be visible given the sensitivity limit of the detector.

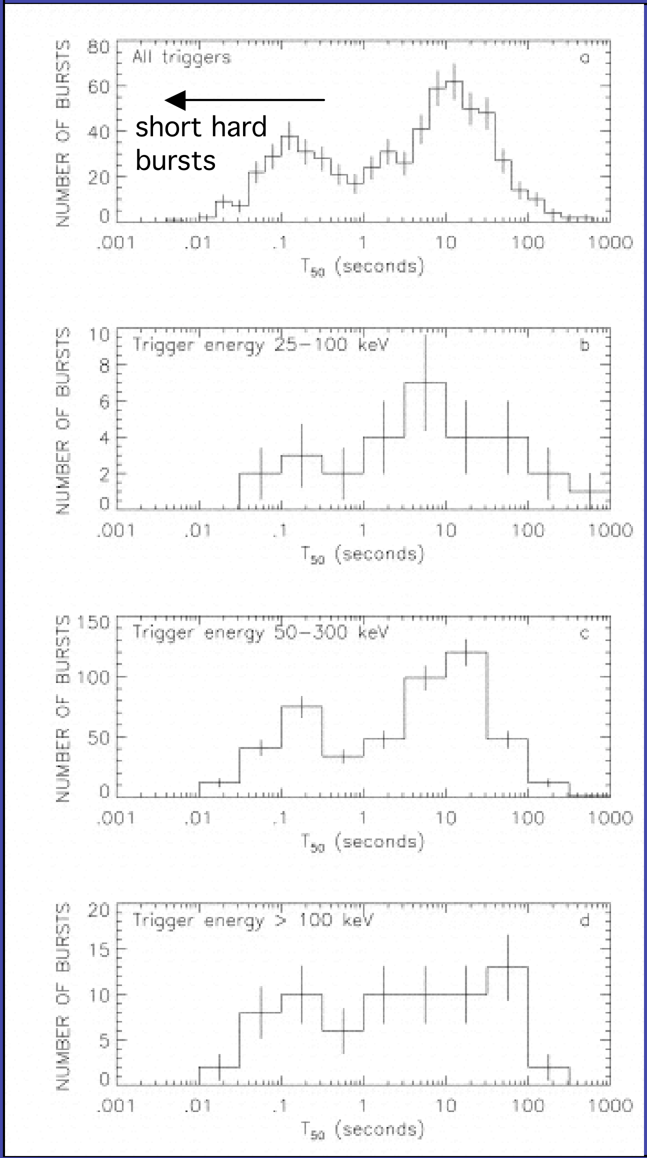
For a uniform distribution of sources throughout the volume, $\langle V/V_{max} \rangle = 0.5$

Subset	Trigger Energy (keV)	Number of Bursts	V/V_{max}
4Br, channels 1 + 2...	25–100	43	0.357 ± 0.045
4Br, channels 2 + 3...	50–300	740	0.324 ± 0.011
4Br, channels 3 + 4...	>100	103	0.345 ± 0.029
4Br, channels 1 + 2 + 3 + 4...	>25	25	0.398 ± 0.061
Full 3B...	50–300	658	0.329 ± 0.011
Full 4Br...	Various	911	0.330 ± 0.010

$\langle V/V_{max} \rangle < 0.5$

Burst radial spatial distribution is cut off

Observational Properties: Timescales



Bursts triggers are bimodal: some very fast, some much longer

Two discrete populations?

Short-timescale variability implies that sources are compact ($R \sim c\delta t$)

BATSE sees about 1/3 of all bursts: true burst rate about 3 per day

Distance Distribution Reconsidered

Cosmological: satisfies BATSE constraints on spatial distributions (cutoff natural due to cosmological redshift in the expanding Universe); but energy budget problem (exacerbated by source compactness)

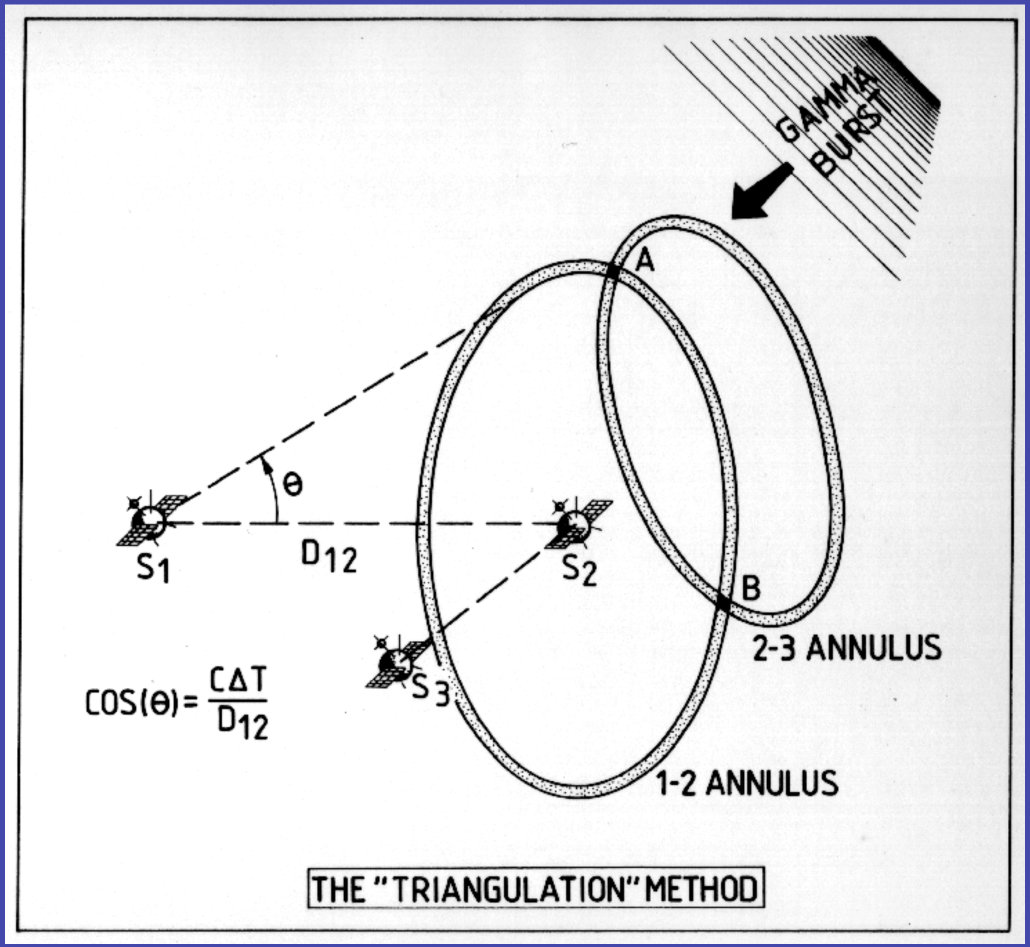
Galactic Halo: high-velocity neutron stars can escape the galaxy; SGRs known neutron stars; cyclotron lines reported for some bursts suggest large B fields if real; could satisfy BATSE constraints; no energy/compactness problem

Interplanetary Network

IPN: uses fleet of GR detectors to constrain GRB positions using triangulation

Each pair of spacecraft, like S1 and S2, gives an annulus of possible arrival directions whose center is defined by the vector joining the two spacecraft, and whose radius theta depends on the difference in the arrival times divided by the distance between the two spacecraft.

By timing the arrival of a burst at several spacecraft, its precise location can be found. The farther apart the detectors, the more precise the location.



http://www.ssl.berkeley.edu/ipn3/

IPN Members

Ulysses: GRB experiment on solar observatory

KONUS/WIND: GRB detector on a solar wind probe

HETE-2

2001 Mars Odyssey

INTEGRAL: International Gamma Ray Astrophysics Lab

RHESSI: Solar high energy observatory

Even with this large effort, proved extremely difficult to find convincing GRB counterparts.

Next Leap

Progress required identification of counterparts

- required small error boxes
- hard to get with GR telescopes
- what about GR + (other) telescope, where (other) is a telescope with good spatial resolution (optical, IR, UV, X-ray)
- *Do GRBs emit in other wavebands?*

BeppoSAX: Big Breakthrough

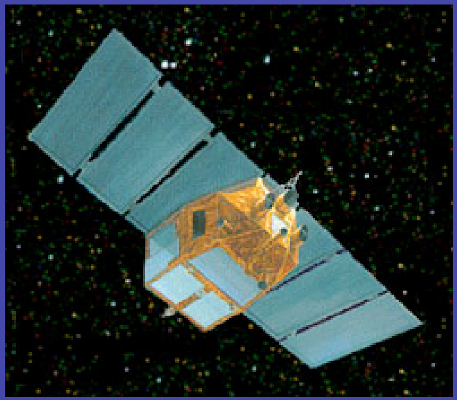
BeppoSAX (1996-2002)

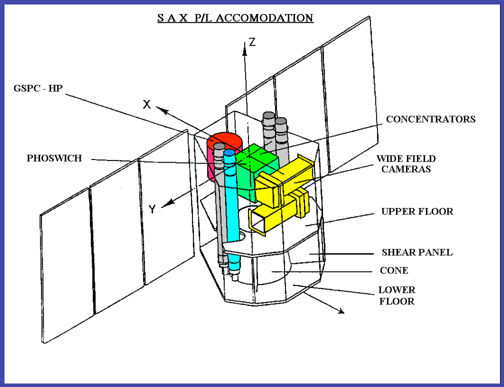
Italian/Netherlands X-ray/Gamma-ray satellite observatory

Energy range 0.1-200 keV

Instruments:

- Narrow Field instruments:
  MECS & LECS: Imaging X-ray spectrometers, 0.1-10 keV
  HGSPC: non-imaging scintillation counter, 4-120 keV
  PDS: collimated Phoswich detector, 15-300 keV;
- Wide Field Cameras: 2 coded mask proportional counters, 2-30 keV, fov 20° x 20°, resolution 5’, perpendicular to the NFI
- Gamma-Ray Burst Monitor: anti-coincidence shields of the PDS, 60-600 keV

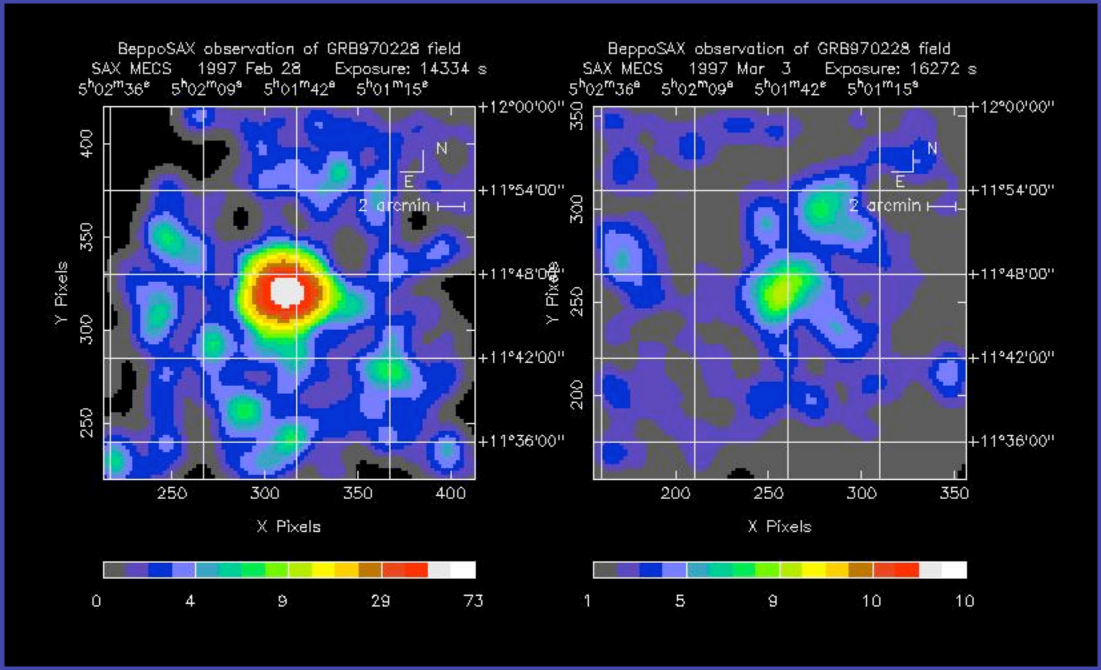




BeppoSAX Afterglows

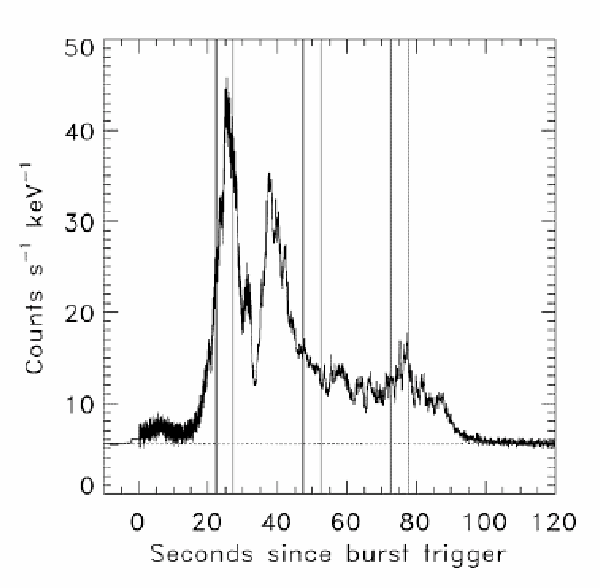
Jan 97 - SAX detected a GRB, imaged with X-ray telescopes within 16 hours of burst (previous record: 18 days)
Feb 97, 5am - SAX detects GRB 970228 in GRBM and in WFCs.

- Repointed SAX to image the GRB field in the NFI within 8 hours.
- X-ray sources seen in the MECS, imaged to within 0.01 degree.
- Followup 2 days later showed a factor of 20 drop in source X-ray flux
- 1st counterpart of a GRB in any waveband



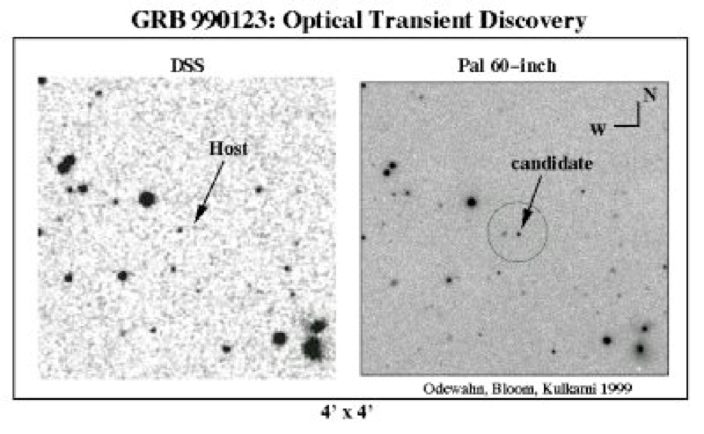
Captured in the Act

Rapid Optical Transient Search Experiment: set of small wide-field robotic telescopes. After a burst the telescopes are notified and slew to the position of the burst (if possible).



ROTSE-1 images
GRB 990123

Dr. Carl Akerlof
University of Michigan
and
ROTSE collaboration



GRB990123: observed by ROTSE about 20 seconds after burst start.
1st (earliest) GRB seen optically in outburst
Became as bright as m_V~8.9 mag
Galaxy counterpart has a redshift z=1.6
If burst in the Milky Way would have made night bright as day.

Timescales in Different Bands

Band	Variability Timescale
Gamma Ray	<minutes
X-ray	days; brightness goes as $t^{-\alpha}$, with $\alpha \sim 1.3$
Optical	days; similar power-law decline ($\alpha \sim 1.4$); flattens at long time (start to detect host galaxy?)

Hosts

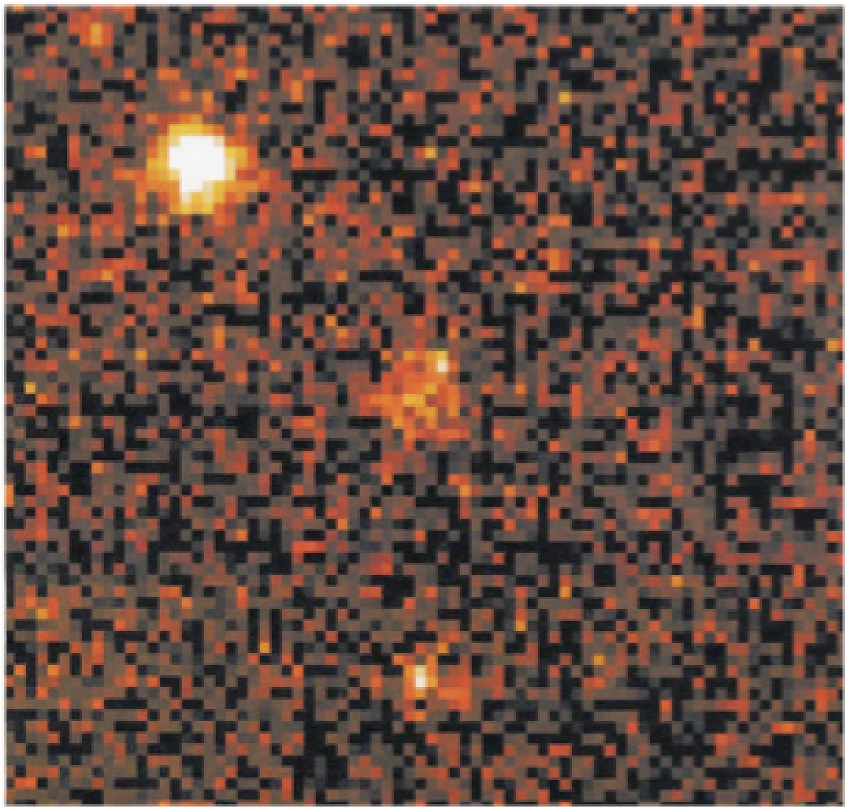


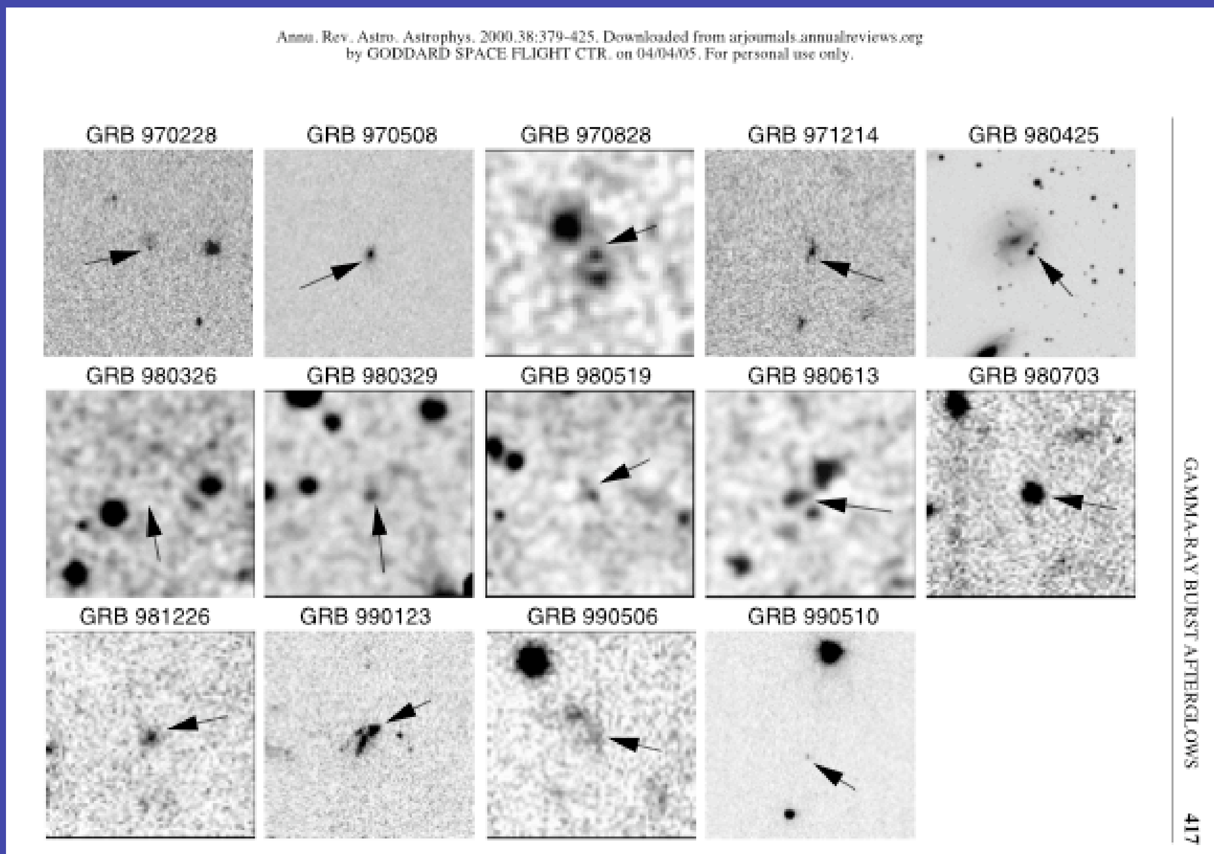
Figure 6 The host galaxy of GRB 970228 (*center*), imaged with HST. The six-month-old afterglow is still visible (*bright pixel*) at the top right edge of the host (Fruchter et al 1999).

Annu. Rev. Astro. Astrophys. 2000.38:379-425. Downloaded from arjournals.annualreviews.org by GODDARD SPACE FLIGHT CTR. on 04/04/05. For personal use only.

HST followup observation with WFPC2 of error box of GRB 970228, in Aug 97.
optical afterglow of GRB still visible (barely)
extended source: galaxy

GRB associated with a galaxy with redshift z=0.695
COSMOLOGICAL

More Hosts



van Paradijs, Kouveliotou, Wijers, 2000, ARAA, 38, 379

Transients tend to be offset wrt centers of host galaxies

Star forming regions?

Host Redshifts

GRB	z (Redshift)	Distance, Gpc
970508	0.835	4
971214	3.42	4.6
970329[1]	5(?)	4.9(?)
970425[2]	0.008(?)	0.04(?)
980613	1.096	3.1
980703	0.966	2.9
990123	1.61	3.7

1. Not measured spectroscopically
2. =SN1998bw?

$$\frac{\lambda}{\lambda_0} = \sqrt{\frac{1+\beta}{1-\beta}} = 1 + z$$

where λ is the observed wavelength and λ_0 the rest wavelength

$$\beta = v/c$$

$$z = v/c \text{ for v<<c}$$

$$r = v/H_0$$

$$H_0 = 71^{+4}_{-3} \text{ km s}^{-1} \text{ Mpc}^{-1}$$

from WMAP

http://online.itp.ucsb.edu/online/gamma_c99/hurley/oh/18.html

Fireball model

Define Compactness parameter:

$$\theta_* = \frac{L\sigma_T}{m_p c^3 (c\delta t)} \simeq \frac{F_\gamma d^2 \sigma_T}{m_p c^4 \delta t} \sim 10^{16} F_\gamma d^2_{Gpc}/\delta t_{ms}$$

Cavallo & Rees 1978

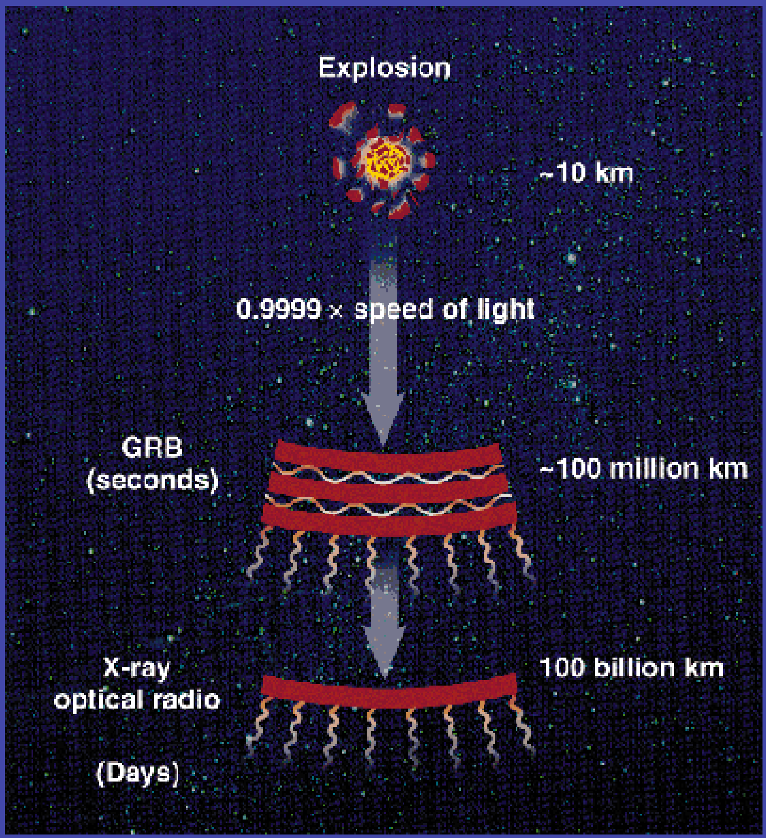
If $\theta_* > 1$, source is optically thick to $\gamma-\gamma$ interactions and not a source of MeV photons, unless source within a distance of 1 kpc or source expanding relativistically

So if sources really are at $z \geq 0.5$, then must be associated with relativistically expanding explosion

Fireball model:

- an explosion produces a bulk flow with v~c produces
- particles are accelerated in a strong shock when the flow meets the circumsource medium
- particle acceleration produces gamma rays.

Fireball cartoon



Similar to standard supernovae, EXCEPT outflow has v/c~1, rather than v<0.1c for standard supernovae

Some timescales:

$$t_{dec} = 63(E_{52}/n)^{1/3}\gamma^{-8/3}\ \mathrm{s}$$

Decelerates in seconds vs. centuries for normal SNe

Evolution becomes similar to “normal” SNe after

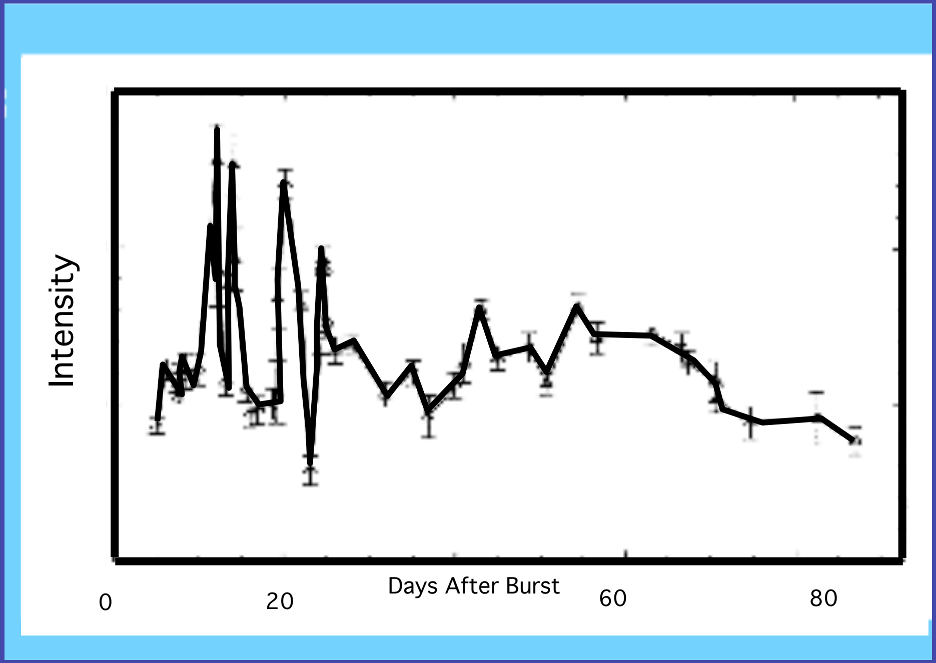
$$t_{NR} = 1.2(E_{52}/n)^{1/3}\ \mathrm{yr}$$

Fireball model confirmed

GRB 970508 observed in radio with the VLA (Frail et al. 1997)

early emission shows evidence of scintillation (“twinkling”)

late emission shows no radio scintillation: implies that the source has become too big to twinkle



Intrinsic Luminosities

ENERGIES AND DISTANCES

GRB	z (Redshift)	Distance, Gpc	Energy if isotropic, erg
970508	0.835	4	7×10^{51}
971214	3.42	4.6	3×10^{53}
970329[1]	5(?)	4.9(?)	5×10^{54}(?)
970425[2]	0.008(?)	0.04(?)	8×10^{47}(?)
980613	1.096	3.1	5×10^{51}
980703	0.966	2.9	8×10^{52}
990123	1.61	3.7	2×10^{54}

1. Not measured spectroscopically
2. =SN1998bw?

redshifts of host galaxies plus observed fluxes imply large isotropic energies, where

$$E_{isotr.} = f_\gamma 4\pi D^2 \delta t$$

Beaming

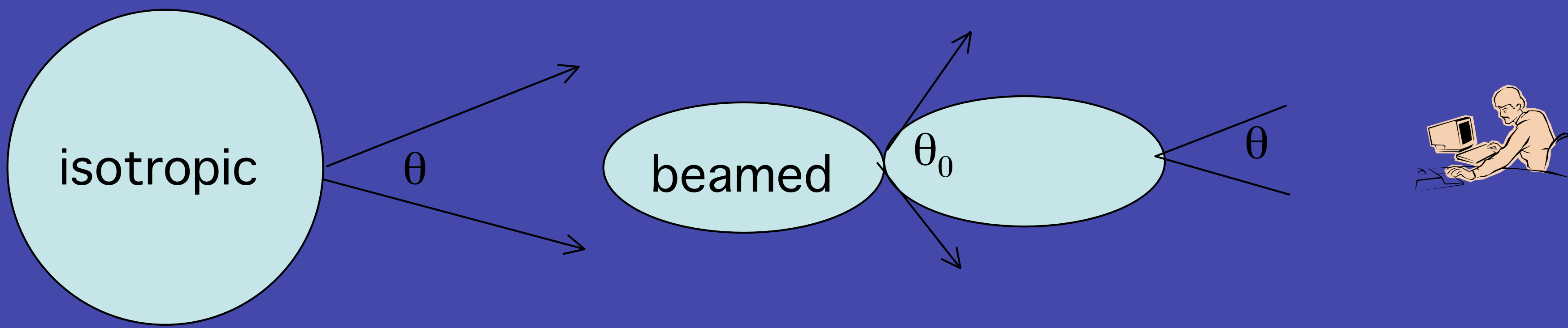
Energetics can be a problem: isotropic energies extremely large - unclear if any model can generate $E \sim 10^{54}$ ergs

Perhaps emission not uniform over all solid angles: *beaming*

For beamed emission, energy emitted into some solid angle $d\Omega < 4\pi$ such that

$$E_{beamed} = f_\gamma d\Omega D^2 \delta t$$

Determining Beaming Fractions



for an emitting surface expanding with a Lorentz factor Γ, an observer is only sensitive to emission within an angle $\theta \sim 1/\Gamma$

So for an expanding decelerating shell, as Γ drops, more of the emission can be seen.

For collimated emission, as Γ drops more of emission can be seen, up to some limit $\theta=\theta_0$

Differences between the two cases can be determined by watching the long-term evolution of the lightcurve

$\Rightarrow$ beaming fractions $d\Omega/4\pi \sim 0.1$

Importance of Beaming

Knowledge of the amount of beaming is important for:

- determining GRB mechanism (highly collimated jet, or spherical blast wave?)
- determining burst frequency: if highly beamed number of GRBs must be much higher than we observed (since we should only observe emission beamed towards us)

Production of Beamed Emission

If collapsars produce the fireball, recent simulations suggest that the initial blast wave from the collapse to a BH could be highly collimated: Jet Driven Supernova

requires rapid core spin just prior to collapse: binary star coalescence?

Standard Candles?

GRBs would be useful standard candles since they're very bright: SNIa can be seen "only" out to z~1.7 with HST, while GRBs have z > 2

Ghirlanda et al. (2004) found a relation between the energy at which the peak of the GRB spectrum occurs and its collimation-corrected energy:

$$E_\gamma = 4.3 \times 10^{50} (\frac{E_{peak}}{267 \text{ keV}})^{1.416 \pm 0.09} \text{ ergs}$$

Caveats: few GRBs with redshifts; how accurate are beaming fractions known? etc

Soft Gamma-Ray Repeaters

4 Soft Gamma-Ray repeaters are known

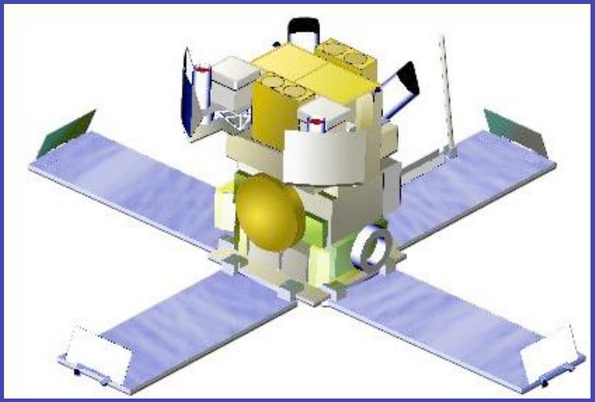
SGR	Description
SGR0525-66	March 5 1979 burst; in SNR N49 in LMC
SGR1627-41	in Galactic SNR
SGR1900+14	in Galactic SNR; burst on 1998 Aug 27 previous record holder
SGR1806-20	Dec 27, 2004: most luminous SGR yet recorded (L_{peak}~2 x 10^{47} erg/s)

HETE2

Launched Oct 9 2000
3 instruments:
FREGATE (6-400 keV) energy range.
Timing and spectra.

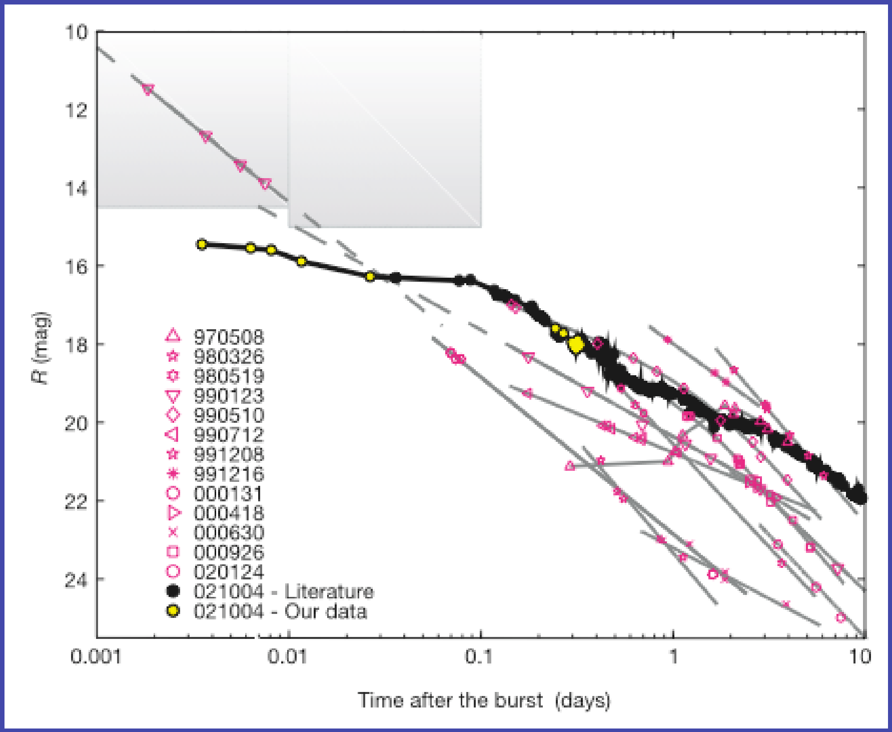
The Wide-field X-ray Monitor (WXM, 2-25 keV) good energy resolution and localization accuracy to ~10' or better.

The soft X-ray camera (SXC) (0.5-10 keV) energy range, with very good energy resolution and localization accuracy to <30"



HETE-2 Results

GRB 021004: SXC position allowed quick optical followup, showed anomalously slow decline in R band, requiring varying energy content in the blast wave early on. Signature of a collapsar?



Swift

Results (So Far)

26 Bursts since Dec 2004 (15 XRT followups)

Swift GRBs with redshifts

GRB	z
GRB 050401	2.9
GRB 050319	3.24
GRB 050318	1.44
GRB 050315	1.949
GRB 050126	1.29

Swift Science data released April 5

see

http://heasarc.gsfc.nasa.gov/docs/swift/swiftsc.html

GCN

Distribution of GRB info from Swift and other satellites to observers on the ground done using the Gamma Ray Burst Coordinates Network (GCN)

The GCN

1. alerts observers to the locations of GRBs detected by spacecraft (some in real-time while the burst is still bursting, but others are delayed due to telemetry down-link delays).
2. distributes reports follow-up observations made by ground-based optical and radio observers.

see http://gcn.gsfc.nasa.gov/

Burst Alerts

Spacecraft (eg Swift) detects a GRB in one or more instruments

Burst is localized (if possible) onboard

Burst position telemetered to GCN via TDRSS

GCN sends out notification to observers via pager, e-mail, blackberry, etc

GCN alerts automated telescopes (ROTSE etc)

the hunt begins...

Summary

Two types of bursts: short, hard bursts & long, complex bursts. Two separate populations, or dichotomy in a single population?

Collapsar model for long bright bursts not falsified: supported by energetics, location of bursts in identified host galaxies, perhaps beaming fraction (at least for some types of bursts)

Need better statistics: better positions: more redshifts

Need quick announcements for followups

Are they standard candles?

What's the universal birth rate of black holes vs age of Universe?